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The long-term goals of this project are to improve and refine understanding of the dynamics of tropical-cyclone structure and intensity change, with emphasis on the role of environmental dynamical effects on the intensity-change process. This project builds upon the experience of the principal investigator in the study of extratropical cyclone dynamics in maritime regions during the past decade, and the recognition that extratropical maritime cyclones bear similarities to their tropical counterparts. Accordingly, a guiding theme of this research effort is to apply and extend well-established dynamical perspectives on extratropical maritime cyclogenesis and cyclone life cycles to the tropics. The long-term goals of this project have been addressed through diagnostic and modeling investigations of: (i) the origin and evolution of tropopause-based precursor disturbances that culminate in rapid maritime cyclogenesis over the western North Atlantic Ocean; (ii) the roles of trough interactions in tropical-cyclone intensity change with a view toward determining the factors that distinguish between cyclogenetic and cyclolytic trough interactions; (iii) the roles of environmental dynamical effects in tropical-cyclone structure and intensity change; (iv) the kinematics of vorticity asymmetries associated with nondivergent barotropic vortices on a beta-plane.

14. SUBJECT TERMS beta-gyres, intensity change, precursor disturbances, rapid maritime cyclogenesis, shallow-water model, tropopause, trough interactions

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ABSTRACT

The long-term goals of this project are to improve and refine understanding of the dynamics of tropical-cyclone structure and intensity change, with emphasis on the role of environmental dynamical effects on the intensity-change process. This project builds upon the experience of the principal investigator in the study of extratropical cyclone dynamics in maritime regions during the past decade, and the recognition that extratropical maritime cyclones bear similarities to their tropical counterparts. Accordingly, a guiding theme of this research effort is to apply and extend well-established dynamical perspectives on extratropical maritime cyclogenesis and cyclone life cycles to the tropics. The long-term goals of this project have been addressed through diagnostic and modeling investigations of: (i) the origin and evolution of tropopause-based precursor disturbances that culminate in rapid maritime cyclogenesis over the western North Atlantic Ocean; (ii) the roles of trough interactions in tropical-cyclone intensity change with a view toward determining the factors that distinguish between cyclogenetic and cyclolytic trough interactions; (iii) the roles of environmental dynamical effects in tropical-cyclone structure and intensity change; (iv) the kinematics of vorticity asymmetries associated with nondivergent barotropic vortices on a beta-plane.

KEYWORDS

beta-gyres, intensity change, precursor disturbances, rapid maritime cyclogenesis, shallow-water model, tropopause, trough interactions

SUMMARY OF COMPLETED WORK

The long-term goals of this project have been addressed through diagnostic and modeling investigations of various aspects of extratropical maritime cyclone dynamics and tropical-cyclone intensity change. In the following summary of completed work, the main results of each investigation are introduced in a "header statement," and then are elaborated upon in subsequent paragraphs.

i. Origin and evolution of tropopause-based precursor disturbances

The planetary-scale environment for rapid cyclogenesis over the western North Atlantic Ocean has been documented using a series of composites based on a 12-season sample of 42 cyclones.

Composite analyses for a six-day period bracketing the onset time of rapid cyclogenesis over the western North Atlantic Ocean reveal a planetary-scale environment characterized by several statistically significant anomaly patterns. Persistent features are a North Pacific trough, an enhanced Pacific jet, and a strong troposphere-deep ridge over western North America. Transient features of the composite include two predecessor troughs, a strong cyclogenetic trough associated with rapid surface deepening, and an upper-tropospheric jet streak west of the developing cyclogenetic trough. These features evolve east of the persistent western North American ridge in an environment characterized by northwesterly flow. The western ridge is important to the development of upper precursor disturbances and western North Atlantic cyclogenesis in that (a) it initiates the development of an elongated jet–front system through frontogenetical processes, and (b) it helps to steer amplifying upper precursors southeastward toward warm Gulf Stream waters, increasing the likelihood of vertical coupling between upper and lower disturbances and resulting cyclogenesis.

The life cycles of 18 upper-tropospheric precursor disturbances that culminated in rapid cyclogenesis over the western North Atlantic Ocean during ERICA have been documented in detail.

Examination of the life cycles of 18 upper-tropospheric precursor disturbances (for surface cyclogenesis) reveals that a subset of these disturbances exhibits amplification in frontogenetical northwesterly flow east of the axis of a ridge over western North America. These events are characterized by an initially elongated region of lower dynamic tropopause that compacts into a more circular configuration prior to crossing the East Coast. The more circular upper-trough configuration, in conjunction with reduced static stability in the offshore environment, allows effective vertical penetration of flow induced by the upper-level potential vorticity maximum into the lower troposphere, resulting in strong cyclogenesis. Diagnosis of these "compacting trough" events reveals that: (a) an essential element of the evolution is a midtropospheric jet–front that intensifies in northwesterly flow downstream of the western ridge, (b) ageostrophic circulations associated with the jet–front materially deform the dynamic tropopause, resulting in a steepening and lowering of the tropopause prior to lower-tropospheric cyclogenesis, and (c) tilting is an important vorticity-generation mechanism in the upper disturbance.

A representative event that occurred during second intensive observation period (IOP 2) of the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA, December 1988–February 1989) has been analyzed from the perspective of local energetics.

A characteristic life cycle of upper-tropospheric cyclogenetic precursors involves the development of an elongated region of lower dynamic tropopause that forms in association with an intensifying midtropospheric jet/front. A representative event of this type that occurred during ERICA IOP 2 has been examined from the perspective of local energetics, allowing determination of the mechanisms that led to jet streak intensification and documentation of the three-dimensional eddy kinetic energy (EKE) distribution within the developing jet/front system. Analysis of the Reynolds stress reveals that the contribution of this term is determined primarily by the relative orientation of the perturbation horizontal wind velocity and the dilatation axis of the time-mean flow. In regions where the perturbation wind velocity is oriented within 45° of normal to the dilatation axis of the time-mean flow, the contribution of the Reynolds stress to the EKE tendency is positive. The presence of a ridge over western North America favors jet streak intensification through the Reynolds stress as northerly perturbation flow east of the ridge axis possesses a favorable orientation with respect to the dilatation axes of the time-mean flow over central North America. Local EKE increases accompany strengthening transverse divergent circulations, facilitating the downward advection of stratospheric values of potential vorticity and eventually resulting in the development of a mobile upper trough. This sequence is consistent with the preference for mobile upper-trough genesis over central North America in the presence of a northerly flow component, a finding documented previously by Sanders.

ii. Roles of trough interactions in tropical-cyclone intensity change

The trough interaction event that led to the reintensification of Hurricane Elena on 1 September 1985 has been analyzed and interpreted using potential vorticity and ageostrophic circulation diagnostic methodologies.

Diagnostic perspectives based on potential vorticity (PV) and ageostrophic circulations (ACs) have been used extensively to reveal signatures of interactions between tropopause- and surface-based disturbances during midlatitude cyclogenesis. PV and AC perspectives have been applied to develop complementary interpretations of the trough interaction event that led to the reintensification of Hurricane Elena on 1 September 1985. From the PV perspective, the trough interaction leading to the reintensification of Elena occurred on the equatorward end of a positively tilted upper-level trough associated with a Rossby-wave breaking event. The location of Elena with respect to the trough is consistent with intensification through PV superposition, whereby the close approach of discrete PV anomalies results in an increase of total perturbation energy in the volume containing these anomalies. Intensification is hypothesized to occur through air–sea interaction instability. From the AC perspective, a well-defined upper-level jet streak was oriented southwest–northeast on the downstream side of the trough, placing Elena in the right-entrance region of the jet streak. The location of Elena with respect to the jet streak is consistent with intensification through divergence situated over the tropical cyclone. Intensification is hypothesized to occur through an enhanced low-level circulation that develops in response to vortex stretching associated with convergent inflow toward the tropical-cyclone center. The enhanced low-level circulation is expected to lead to increased surface fluxes of heat

and moisture, consistent with the occurrence of air–sea interaction instability as in the PV perspective.

Consideration of all named tropical cyclones that occurred over the North Atlantic basin from 1985 through 1996 has led to a proposed classification scheme for tropical-cyclone intensity change that consists of six characteristic types.

Previous case studies performed as part of this effort have shown that favorable trough interactions are characterized by relatively small-to-moderate values of vertical wind shear associated with shallow potential vorticity (PV) anomalies. When PV anomalies are restricted to the outflow layer of the tropical cyclone, diabatic erosion of PV can weaken the PV anomaly and thereby diminish the vertical wind shear in the vicinity of the tropical cyclone. In contrast, unfavorable trough interactions are characterized by large values of vertical wind shear associated with deep PV anomalies that extend below the layer where diabatic heating can reduce the strength of the PV anomaly.

The foregoing preliminary findings are extended to a larger sample of cases by considering all named tropical cyclones that occurred over the North Atlantic basin from 1985 through 1996. A trough interaction event is defined where the eddy flux convergence (EFC) at 200 hPa over a 300–600 km storm-centered radial band exceeds 10 m s^{-1} d^{-1} and the total surface pressure change during the interaction exceeds 10 hPa. Consideration of the larger sample of cases has resulted in a classification scheme for tropical-cyclone intensity change. In the first four categories of this scheme the tropical cyclone intensifies, whereas in the fifth and sixth the tropical cyclone weakens. The first, second, third, and fifth categories satisfy the definition of a trough interaction, whereas the fourth and sixth do not involve the presence of a trough. The categories are: (a) superposition (upper-tropospheric positive PV anomaly within 400 km of storm center); (b) distant interaction (PV anomaly between 400 and 1000 km of storm center); (c) extratropical transition (intensification following transition); (d) favorable/no trough (intensification with EFC less than 5 m s^{-1} d^{-1} for at least three consecutive 12 h periods); (e) unfavorable trough interaction (weakening with enhanced EFC); and (f) unfavorable/no trough (weakening with EFC less than 5 m s^{-1} d^{-1} for at least three consecutive 12 h periods). Composites for each of these characteristics types of tropical-cyclone intensity change have been calculated. The respective composites are being analyzed in further detail using Eliassen–Palm flux diagnostics and a decomposition of the wind field into rotational and divergent parts.

iii. Roles of environmental dynamical effects in tropical-cyclone structure and intensity change

An idealized three-layer shallow-water numerical model has been applied to investigate the effect of zonal background flows on the intensification of tropical-cyclone-like vortices for f- and β-plane geometries.

The effect of uniform zonal background flows on the intensification of tropical-cyclone-like vortices is investigated using a numerical three-layer shallow-water model that includes parameterizations of convection, sea surface energy exchange, and boundary-layer friction. Calculations on an f-plane show that during the developing stage, an initially weak vortex intensifies more rapidly in the presence of a uniform zonal background flow. Compared to

an environment at rest, the uniform zonal background flow results in increased boundary-layer convergence colocated with increased boundary-layer mixing ratio due to surface moisture fluxes, producing stronger convection and therefore more rapid intensification. After the vortex achieves hurricane strength in the presence of an easterly (westerly) background flow, a region of convectively stable air forms to the south (north) of the vortex center as a result of low surface moisture fluxes and the downward transport of relatively dry middle-layer air. This convectively stable air penetrates slowly into regions of boundary-layer convergence, thereby weakening convection and reducing the maximum intensity of the vortex. This effect is found to be more pronounced for stronger uniform background flows.

Calculations on a β-plane show that a westerly background flow is more favorable for intensification than an easterly background flow of the same strength. This dependence of intensification rate on the direction of the background flow is shown to be due to differences in the position of a region of convectively unstable air relative to the trajectory of the vortex in these respective cases. In the westerly background flow case, the vortex always moves into a region of convectively unstable air, whereas in the easterly background flow case, the vortex progressively moves into a region of convectively stable air produced by subsidence and drying of the boundary layer. Because of the relatively high vortex drift speed in the easterly background flow case, there is not sufficient time for surface moisture fluxes to moisten the dry boundary-layer air rapidly enough to eliminate the convectively stable region ahead of the vortex, resulting in the overall weakening of convective activity and a less intense storm than in the westerly flow case. The foregoing calculations suggest that the imposed background flow affects the development of the vortices in the shallow-water model by establishing an environment in which boundary-layer convergence and surface moisture fluxes may interact to produce stratifications that either enhance or suppress convection, which ultimately controls the intensification of the vortices in the model.

iv. Kinematics of vorticity asymmetries associated with nondivergent barotropic vortices on a β-plane

A diagnostic methodology has been developed for characterizing the anisotropy of nondivergent flow fields in a pointwise sense and illustrated for β-gyres in a barotropic model of a tropical-cyclone-like vortex.

A diagnostic methodology has been developed for characterizing the anisotropy of nondivergent flow fields in a pointwise sense and is applied to the β-gyres in a barotropic model of tropical-cyclone-like vortices. This methodology makes uses of a new type of natural-coordinate system motivated by Petterssen's classic treatment of linearly varying horizontal wind fields, where the coordinate axes are oriented along and across the locally preferred direction of a flow feature. In this application, the relative vorticity field is partitioned into components associated with the along- and across-gyre directions, such that the across-gyre vorticity is a maximum relative to the along-gyre vorticity in a pointwise sense. These respective vorticity fields may be inverted to yield flows over the vortex center, quantifying the influence of the anisotropy of the β-gyres on vortex motion. The partition of vortex motion into along- and across-gyre components indicates the dominance of the latter, consistent with the azimuthally elongated structure of the vorticity asymmetries that induce the β-gyres. The potential significance and novelty of this diagnostic methodology is that it offers a framework for relating the strength and configuration of the flow induced

by a vortex to its anisotropy, which now may be quantified locally instead of globally (i.e., in terms of a single aspect ratio characterizing the entire vortex). This capability may prove useful in diagnosing vertical interactions among vortices during tropical-cyclone intensity change, since the strength of vertical coupling is hypothesized to be related to vortex anisotropy. Moreover, the proposed methodology is not restricted to the present application, which is concerned with nondivergent wind fields, but may be generalized to apply to horizontal wind fields containing divergence on both regional and global domains. The further possibility exists to modify the proposed methodology to determine the preferred directions of vertical velocity and pressure tendency patterns.

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PROJECT PERSONNEL

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